The Polar Wind and the Terrestrial Helium Budget

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A problem exists concerning the escape of the helium isotopes He^3 and He^4 from the earth's atmosphere. The essential difficulty is that the escape of He^4 cannot be purely thermal, but all nonthermal mechanisms which have been considered to date fail to produce the necessary loss rate by a wide margin [*Nicolet*, 1957; *Bates and McDowell*, 1957, 1959; *Kockarts and Nicolet*, 1962; *MacDonald*, 1963]. In this letter we suggest a new mechanism which might resolve the problem and which has the interesting implication that it relates the escape of helium to other phenomena, notably the formation of the plasmapause [*Gringauz et al.*, 1960; *Gringauz*, 1963; *Carpenter*, 1963, 1966; *Taylor et al.*, 1965, 1968; *Binsack*, 1967; *Angerami and Carpenter*, 1966; *Serbu and Maier*, 1966], and the peculiar behavior of the ionosphere at high latitudes [*Hagg*, 1967; *Muldrew*, 1965; *Brace and Reddy*, 1965; *Barrington et al.*, 1966; *Donley*, 1967; *Brace et al.*, 1967; *Thomas et al.*, 1966; *Hill*, 1960; *King*, 1961].

The basic data are the following (e.g., *MacDonald* [1963]): The rate of production of He^4 by the radioactive decay of uranium and thorium in the Earth's crust is

$$P(He^4) = 10^6 - 3 \times 10^6 \text{ atoms cm}^{-2} \text{ sec}^{-1},$$
$$= 5 \times 10^{24} - 1.5 \times 10^{25} \text{ atoms sec}^{-1}$$

The rate of accumulation of He^3 by accretion of solar and galactic cosmic ray He^3 nuclei, and by decay of tritium produced by cosmic ray interactions in the atmosphere is

$$P(He^3) = 0.5 - 5 \text{ atoms cm}^{-2} \text{ sec}^{-1}$$
$$= 2.5 \times 10^{18} - 2.5 \times 10^{19} \text{ atoms sec}^{-1}$$

The total concentration of He^4 in the atmosphere is $Q(He^4) = 1.13 \times 10^{20}$ atoms $cm^{-2} = 5.6 \times 10^{38}$ atoms. The total concentration of He^3 in the atmosphere is $Q(He^3) = 1.41 \times 10^{14}$ atoms $cm^{-2} = 7 \times 10^{32}$ atoms. From these data the minimum times required to accommodate the present concentrations of the two isotopes are $T(He^4) = Q(He^4)/P(He^4) = 1.2 \times 10^8 - 3.6 \times 10^8$; $T(He^3) = Q(He^3)/P(He^3) = 9 \times 10^5 - 9 \times 10^6$ years. Note that the value of $P(He^4)$ is uncertain to within a factor of about 50% of the value 2×10^6 atoms cm^{-2} sec^{-1} adopted by *MacDonald* [1963] (see also *Kockarts and Nicolet* [1962]). MacDonald favors a value of 10 atoms cm^{-2} sec^{-1} for $P(He^3)$, but the main contribution to this estimate is due to accretion of solar cosmic rays, assuming 10 per cent to be He^3 nuclei, which seems much too large (cf. *Fichtel* [1967]]). It is, however, certain that the rate of production of tritium by cosmic rays is 0.20 ± 0.05 atom cm^{-2} sec^{-1} [*Teegarden*, 1967], which is a safe lower limit for $P(He^3)$; in addition perhaps 0.1 atom cm^{-2} sec^{-1} are accreted directly from the galactic cosmic radiation (e.g., *Biswas et al.* [1967]). The capture of He^3 nuclei from the solar wind as it flows past the magnetosphere could be an important source of atmospheric He^3; preliminary estimates suggest that this would have a rate consistent with the above values of $P(He^3)$.

The average rate of thermal escape of He^4 atoms from the atmosphere during the last solar cycle has been calculated [*Kockarts and Nicolet*, 1962; *MacDonald*, 1963] to be $L^t(He^4) = 6 \times 10^4$ atoms cm^{-2} $sec^{-1} = 3 \times 10^{29}$ atoms sec^{-1}. For He^3, the average rate of thermal escape is $L^t(He^3) = 3.5$ atoms cm^{-2} $sec^{-1} = 1.8 \times 10^{19}$ atoms sec^{-1}. Note that the rate of escape is a very sensitive function of the temperature of the thermopause [*Kockarts and Nicolet*, 1962], and hence these values could be overestimates, if (as could well be the case) the average thermospheric temperatures are lower than assumed. For a wide range of ionospheric temperatures, the time required for the thermal

escape of He^3 atoms is about one hundredth of the time required for the thermal escape of He^4 atoms. It is clear then because $T(He^3)$ and $T(He^4)$ are comparable and $P(He^3)$ and $L^t(He^3)$ agree reasonably well, that purely thermal escape cannot be the explanation of the problem. If the temperature of the thermopause had been sufficiently elevated in the past to account for the escape of He^4, then the He^3 would have been effectively lost. Hence, the suggestion by *MacDonald* [1963] that the rate of thermal escape of He^4 has been substantially higher in the past is probably incorrect. There is in fact no compelling reason for believing that there has been any significant disequilibrium during the past 10^9 years or so other than the recent destruction of the tritium balance by thermonuclear bomb tests [*Teegarden*, 1967]. We conclude, therefore, that the escape mechanism must be nonthermal and must not favor significantly the isotope with smaller mass. Thus, if $L^{nt}(He^4)$ is the rate of escape of He^4 by nonthermal processes, then $L^{nt}(He^4) + L^t(He^4) = P(He^4)$, and similarly for He^3. Clearly $L^{nt}(He^4) \gg L^t(He^4)$, but it is possible for $L^{nt}(He^3)$ and $L^t(He^3)$ to be of comparable magnitudes.

It has been pointed out by *Nicolet* [1961] that the total rate of photoionization of atmospheric He^4 by solar ultraviolet is approximately the same as $P(He^4)$, and hence that some process involving helium ions might provide the explanation of the escape of both He^4 and He^3 from the atmosphere. Several mechanisms involving ions have been proposed [*Wilson*, 1962; *Bates and Patterson*, 1962] but found inadequate (Patterson, unpublished). In each case the particles were assumed to escape eventually as neutral atoms, since it was thought that ions would remain trapped in the geomagnetic field even if they are given sufficient energy to escape from the gravitational field (1.8 ev for He^3 and 2.4 ev for He^4). However, as pointed out by *Dungey* [1961, 1967] such geomagnetic trapping will not occur in the polar regions of the magnetosphere where the geomagnetic field lines are connected to the interplanetary magnetic field.

At any time one should expect that the geomagnetic field lines which intersect the earth at geomagnetic latitudes (Λ) greater than about 75° are 'open,' corresponding to about 1/40 of the total surface area of the earth. In fact it is not only the field lines which are instantaneously open that are important as far as the loss of low energy charged particles is concerned. It is known that there are large-scale electric fields in the magnetosphere, which implies that the plasma undergoes convective interchange motions [*Axford and Hines*, 1961; *Axford*, 1967]. Hence plasma which is at one time in a region of closed magnetic field lines may later find itself in a region of open field lines, and vice versa. According to *Axford and Hines* [1961] the inner boundary of the high latitude convection system should be expected to lie typically at $\Lambda \approx 60°$. *Carpenter* [1962] has suggested that the whistler 'knee,' or plasmapause, coincides with this boundary, and on combining this suggestion with Dungey's one obtains a very plausible explanation for the formation of the plasmapause. Indeed, *Nishida* [1966] and *Brice* [1967] have been able to explain the observed shape of the plasmapause on the basis of convection patterns of the type described by Axford and Hines, and the changes in the position of the plasmapause which take place during geomagnetic storms [*Carpenter*, 1966; *Angerami and Carpenter*, 1966; *Binsack*, 1967; *Taylor et al.*, 1968] are consistent with such an explanation.

If it is assumed that every helium ion produced in the ionosphere above 400 km altitude and at geomagnetic latitudes greater than 60°, eventually escapes from the earth without recombining, then it is a simple matter to estimate the helium loss rates $L^{nt}(He^4)$ and $L^{nt}(He^3)$. The total He^4 content of the atmosphere at altitudes greater than 400 km is 7.6×10^{13} atoms cm^{-2} for an ionospheric temperature of 1400°K [*Nicolet*, 1968]. The photo-ionization rate coefficient for helium is $1.0 \pm 0.5 \times 10^{-7}$ sec^{-1} [*Nicolet*, 1968], and hence the He^{4+} production rate is $(7.6 \pm 3.8) \times 10^6$ cm^{-2} sec^{-1}. Accordingly, the rate of loss of He^4 from the atmosphere is approximately given by

$$L^{nt}(He^4) = (7.6 \pm 3.8) \times 10^6 \text{ atoms } cm^{-2}\, sec^{-1}\ (\Lambda > 60°)$$

$$= (4.4 \pm 2.2) \times 10^{24} \text{ atoms } sec^{-1}$$

which is close to the range of value of $P(He^4)$ quoted above. On performing the same calculations for the case of He^3, assuming that the

total He^3 content of the atmosphere above 400 km altitude is 1.3×10^{-6} that of the He^4 content, it is found that

$$L^{nt}(He^3) = 10 \pm 5 \text{ atoms cm}^{-2} \text{ sec}^{-1} \ (\Lambda > 60°)$$

$$= (6 \pm 3) \times 10^{18} \text{ atoms sec}^{-1}$$

This result suggests that atmospheric He^3 escapes mainly by evaporation of neutrals, since $L^t(He^3)/L^{nt}(He^3) = 2 - 6$. However, as mentioned above, the value adopted for $L^t(He^3)$ could be significantly overestimated.

It can be argued that these results for the nonthermal escape rates of He^3 and He^4 are too large because the optical depth of the atmosphere increases at large solar zenith angles, and also because the atmosphere cannot be entirely illuminated by sunlight in both polar regions at any given time. However, these effects should reduce the estimates for $L^{nt}(He^3)$ and $L^{nt}(He^4)$ at most by only about 50% (near the solstices), and on the average by a somewhat smaller amount.

It is appropriate to take all helium ions into account in these calculations, even if they are initially produced at a relatively low level in the ionospheric F region. At these levels, He^{4+} and He^{3+} are minor ions of relatively low mass and hence are accelerated upward by the vertical electric field produced by the buoyancy of the electrons relative to the dominant ions (NO^+, O_2^+, O^+). Rough estimates suggest that the vertical speeds attained are sufficiently large to carry the ions upward through the ionosphere from the 400 km. level without significant loss. It should be noted that radiative recombination of helium ions takes place extremely slowly (the lifetime is about 3 months for an electron density of 10^5 cm^{-3}). A more important loss mechanism is dissociative charge transfer with N_2 [*Ferguson et al.*, 1964]; the rate coefficient is about 10^{-9} cm^3 sec^{-1}, and hence the mean lifetime of a helium ion at 400 km altitude is of the order of 100 sec, which should be long enough for the ions to move upward through one N_2 scale height on being accelerated by the vertical electric field. In an ionosphere in diffusive equilibrium, the helium ions should collect and 'float' at an altitude where the net force acting on them vanishes (heavier ions (O^+) produced at this altitude should descend and lighter ions (H^+) should ascend); these transport effects appear to be ignored in many treatments of the structure of the ionosphere (e.g. *Mange* [1960]).

In the polar ionosphere where the geomagnetic field lines are open, diffusive equilibrium is unlikely to occur because the plasma can flow out into interplanetary space. However, the loss of plasma is not just what would be expected from evaporation at normal ionospheric temperatures as suggested by *Dessler and Michel* [1966] and by *Nishida* [1966]. In fact, the lighter ions must be dragged away from the earth by the escaping photoelectron flux, and the resulting flow speeds can reach 10 km sec^{-1} or more. The ions are accelerated by the electric field produced by charge separation resulting from the departure of the photoelectrons, and the overall potential difference can easily amount to tens of volts. A photoelectron flux of about 2×10^8 cm^{-2} sec^{-1} with energies greater than 2.4 ev would be sufficient to carry away the H^+, He^{4+} and He^{3+} ions produced in the polar ionosphere. In fact the photoelectron fluxes appear to be much larger than this, even for energies of the order of 35 ev (cf. *Donley*, [1967]) with the result that the energy obtained by the ions may be some tens of ev, and that heavier ions such as O^+ (escape energy = 9.6 ev) also flow out into space. The net result is that the apparent scale height of the topside ionosphere should be abnormally large in regions where the geomagnetic field is open and photoelectrons can escape; the mean ion mass in such regions should be higher than normal for a given altitude. In regions where the field lines have recently been open but are now closed, the photoelectrons cannot escape, and the flow of ions may decrease to the low levels appropriate to thermal diffusion; thus at a given altitude the plasma density should be lower than usual. These effects are entirely consistent with observations made from satellites at altitudes of 1000 km. and higher [*Barrington et al.*, 1966; *Hagg*, 1967; *Thomas et al.*, 1966; *Donley*, 1967] and also provide an explanation for the anomalously low F-region critical frequencies observed in the high latitude ionosphere during daytime [*Hill*, 1960; *King*, 1961].

It is very evident on considering this description of how the ionospheric plasma flows away

from the earth along open geomagnetic field lines that this whole process is closely analogous to the flow of solar plasma away from the sun [*Parker*, 1963]. Hence it is appropriate to call the phenomenon the 'polar wind.' One sees that the plasma (ions plus photoelectrons) is too energetic to be gravitationally bound to the earth and this, together with the condition of zero pressure at infinity, demands that there should be an outward flow of plasma. The flow must eventually become supersonic as a result of the combined effects of the decrease of gravity and divergence of the magnetic field lines with increasing distance from the earth. The tendency for the plasma near the source to become enriched with ions having a high mass to charge ratio is observed to occur in both cases [*Barrington et al.*, 1966; *Pottasch*, 1964]. Calculations recently carried out by *Banks and Holzer* [1968] indicate that these arguments are substantially correct; they have further shown that the effects of ion production and frictional drag play an important part in causing the flow to become supersonic.

The polar-wind flux per unit area must decrease in proportion to the magnetic field strength. Since the flow should be supersonic at altitudes of a few earth radii and more, the density of the polar wind plasma must be extremely low in the tail of the magnetosphere. For example, if only H^+ and He^+ ions escape the flux (φ) is roughly (2×10^8) (B/B_0) cm^{-2} sec^{-1}, where B is the local magnetic field strength and B_0 the field strength at ionospheric levels. Taking $B = 30\ \gamma$ and $B_0 = 6 \times 10^6\ \gamma$, then $\varphi \approx 10^5$ cm^{-2} sec^{-1}, which for a flow velocity of $10 - 10^2$ km sec^{-1} (i.e. particle energies of about 1–10^2 ev) corresponds to a number density less than 10^{-1} cm^{-3}. If the O^+ component of the polar wind is substantial, φ could increase by a factor 10 or more, but even with correspondingly lower flow velocities it is difficult to achieve a number density in the tail of the magnetosphere that approaches 1 cm^{-3}. We suggest that the polar wind should be most easily observable in the altitude range 10,000–20,000 km where the particle flux and number density are still reasonably large and the Mach number not too small for the flow direction to be readily apparent. The most favorable positions for making such an observation would be in the geomagnetic latitude range 75–85°, near local noon, and in summer.

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